DOI: 10.2478/frp-2013-0013

Leśne Prace Badawcze (*Forest Research Papers*),
June 2013, Vol. 74 (2): 127–136.

ORIGINAL RESEARCH ARTICLE

A two-phase inventory method for calculating standing volume and tree-density of forest stands in central Poland based on airborne laser-scanning data

Stanisław Miścicki[1], Krzysztof Stereńczak[2] ✉

[1] Warsaw University Of Life Sciences–SGGW, Department of Forest Management Planning, Geomatics and Forest Economics, ul. Nowoursynowska 159, 02-776 Warszawa, Poland; [2] Forest Research Institute, Department of Information Technology and Modelling, Sękocin Stary, ul. Braci Leśnej, 05-090 Raszyn, Poland

✉ Tel. +48 22 7150325, fax. +48 22 7200397, e-mail: K.Sterenczak@ibles.waw.pl

Abstract. This paper describes a method of determining the stocking density and volume of forest stands based on airborne laser-scanning data. The aim of this study was to determine the relationship between ground-based measurements of standing volume and tree-density, and those acquired based on the Crown Height Model (CHM) interpolated from airborne laser scanning data. Data were collected from 34 sample plots of two sizes for the CHM analysis: 500 m^2 (radius 12.61 m) and 1963.5 m^2 (radius of 25.0 m): Trees for sampling were selected using two methods, those whose "centroid" was fully within the sample plot (the tree was considered to be within the sample plots if the centroid of the crown was inside the circle) and those at the "border" (the tree was included in the sample plot if, at least, one part of the contour of the crown was inside the circle). There was a strong relationship (R^2 = 0.86) between standing volume measured in sample plots on the ground and the indices produced by the crown elevation model at the locations where the ground-based measurements were performed.

Key words: centroid, ground-based data, forest inventory, scaling, airborne ceiling, Crown Height Model

1. Introduction

Calculating standing volume based on airborne ceiling data rests on searching for correlations between measurements obtained from the airborne ceiling display and standing volume ground-based measurements – most often on sample plots of a few hundred square metres. In the past, measurements acquired from airborne photographs have been used (Miścicki 2000, 2009; Korpela i Tokola 2006). Nowadays, measurements, on the larger scale, are used that are obtained from Airborne Laser Scanning data (Naesset 2004; Breidenbach et al. 2007; Hyyppä et al. 2012).

Applying the Airborne Laser Scanning (ALS) in the analyses of forest environment, has been already described in Polish field literature (Będkowski 2004; Wężyk 2006; Chirrek et al. 2007; Stereńczak 2010a). The most important advantages of the method are: obtaining the very accurate Canopy Height Model (CHM), analysing vertical and horizontal forest structure, and some other tree-related parameters. Based on previous experiences, two groups of methods can be identified to determine standing volume. Airborne Laser Scanning data is used to determine:

– variables of single trees for the Individual Tree Detection (ITD) method,
– variables of plots for the area-based approach (ABA).

A type of Airborne Laser Scanning data depends on the method of determining the standing volume. When information about individual trees is used, it is advisable to apply the point cloud ALS of larger density (about 4-5 points per m^2) to separate individual tree crowns. Regarding methods that use features related

Received 3 July 2012, accepted after revision 17 October 2012

to sample plots, it is possible to obtain the point cloud of lower density (about 0,5-1 point per m^2). Advantages and disadvantages of both methods are compared in Table 1.

According to the literature (Korpela, Tokola 2006; Wack 2006; Hyyppä et al. 2012; Straub, Koch 2012), when different models of correlations between standing volume based on the measurements and variables of ground sample plots obtained from Airborne Laser Scanning data is used, the strength of relationship – determined by a correlation coefficient – is R=0,4–0,95. The strongest correlation has been in coniferous stands, especially in spruce stands, and the weakest in deciduous stands (Korpela, Tokola 2006; Wack 2006, Hyyppä et al. 2012). For individual trees in pine stands, a coefficient of determination R^2 was between 0,488 and 0,931 (Straub, Koch 2012). Unfortunately, there are not many publications related to forests in Central Europe. So far, according to published research, each model needs calibration with respect to individual forest stands (Breidenbach et al. 2007). Hence, there is a need for conducting research in Poland and searching for models based on the structure of Polish forests in the best possible manner.

2. Research materials

Ground sample plots

Research materials contain data collected from 34 circular sample plots set up in stands of the Milicz Forest District (Regional Office of State Forests in Wrocław; 51°48' N i 17°33' E) (Fig. 1).

On each plot, the diameter at breast height and height of all trees that qualified for the sample were measured in August 2006. On the bases of polar coordinates, trees' locations in relation to the centre of the sample plot were determined. Coordinates of the centres of sample plots were calculated by the forward differencing method using GPS–Mobil Maper. The mean measurement error was 2 m. On average, the area of sample plots was 391 m^2 that varied (according to the stand age) from 200 to 500 m^2. The average stand age was 85 years (between 15 and 150 years). Tree species' composition was diverse: pine was the dominating species on 16 sample plots, beech – 11, oak – 3, alder – 2, larch – 1, birch – 1. Average level of crown closure was estimated to be 59% (in the range of 20–95%). A general description of data obtained from the sample plots was as follows:

Table 1. Comparison of methods of standing volume estimation with Airborne Laser Scanning technology, with using individual tree detection of area based approach by Hyyppä et al. (2006)

Advantages:	Disadvantages:
Area based method of standing volume estimation (ALS point cloud of density about 0.5–1 p/m^2)	
– easy integration with the current method of forest stock inventory by using the same reference sample plots – strong statistical background – relatively low cost of Airborne Laser Scanner data acquisition	– requires large number of accurate, representative, and thus expensive reference data – a large number of errors in inventory as a result of insufficient number of reliable reference data
Individual tree detection method of standing volume estimation – ALS point cloud of density about 4–5 p/m^2	
– good correlation (existing models) with the estimated stand volume – requires small number of reference data for model calibration – increasing the number of parameters describing the forest, so-called precision forestry	– expensive Airborne Laser Scanner data acquisition – a much more complex system, difficult to apply in practice

For the variable symbols see Figure 3

– average tree height – 23,9 m (in the range of 5–39 m),
– dominant height (calculated as an average of three tallest trees in the sample plot) – 26,1 m (in the range of 5–40 m),
– average tree number (of at least 7 cm of diameter of breast height) in the sample plot – 16,2 (in the range of 0–33), including trees of the first floor – 14,4 (in the range of 0–33),
– average standing volume – 330 m^3/ha (in the range of 0–665 m^3/ha),
– average stem density of at least 7 cm of diameter of breast height – 490 trees per ha (in the range of 0–1300 trees per ha).

Data acquired from the Airborne Laser Scanning

Airborne Laser Scanning data acquired between 2.05.2007 and 3.05.2007 were used in analyses. TopoSys GmbH FALCON II laser scanner of fibre optic, pulse type sensor was used in the research. Length of the wave was 1560 nm. Scanning was performed on the height level of 700 m with 83 kHz frequency, scan angle of ±7,1° from the nadir. The scanner registered the first echo (FE) and the last echo (LE). The ground-based scanning spot diameter was 0,7 m. During the flight, spectral information of R, G, B, and IR channels was obtained using the data scan ruler. Processing pictorial representation of data was done using true-ortophotomap of 0,25 m pixel size.

At the first stage of processing, Airborne Laser Scanning data was used to interpolate Digital Terrain Model (DTM), Digital Surface Model (DSM), and normalized Digital Surface Model (nDSM) (Fig. 2), which is the difference between corresponding pixels in DTM and DSM. In the context of forest, nDSM is called a Canopy Height Model (CHM).

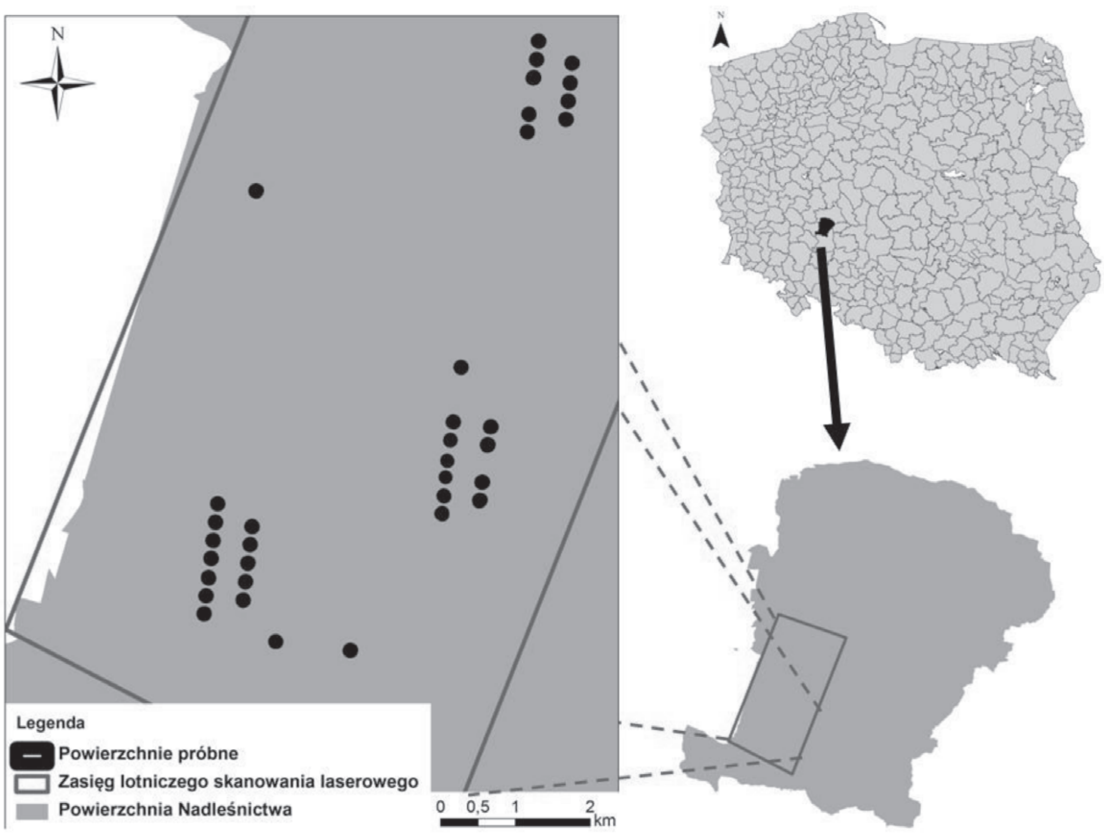

Figure 1. Study area and sample plots location (black dots – sample plots, dark line – border of ALS data acquisition, grey are – Milicz Forest District area).

TreeVis (FELIS Freiburg University) program was applied to filter the point cloud and interpolate Digital Terrain Models. Active contours algorithm (Elmqvist 2000), that is used to filter data point, was implemented.

By using coordinates of sample plot centres in a Canopy Height Model, centres were indicated and circles were formed. Measurements were performed inside the circles. Two sizes of circles were applied: 500 m^2 (radius 12,61 m) and 1963,5 m^2 (radius 25,0 m). It implies that the sample plots defined with the Canopy Height Model were larger (and only sometimes equal) than the ground ones. Two variants of tree qualification for the sample were applied for each sample plot, i.e. “centroid” variant (the tree was considered to be within the plot if the centroid of the crown was inside the circle) and the “border” variant (the tree was included in the plot if, at least, one part of the contour of the crown was inside the circle).

Then, segmentation of tree crowns was performed (Stereńczak 2010b). A Canopy Height Model was applied by conducting following procedures:

– loading a Canopy Height Model and its simplification (smoothing) using a Gaussian filter,
– caring out the first segmentation, generating primary segments,
– calculating crown height layers,
– assigning primary segments to height classes,
– reduction of height classes using a Gaussian filter of different size: higher layers by using larger size, and lower layers by using smaller size (3 height layers were used for which 15 m and 25 m were boundary values, and filter size: 3×3, 5×5, 7×7 pixels).

After separating final segments:

– ranges of individual tree crowns were calculated; in each final segment we determined the maximum value of elevation Z of the point belonging to the crown, and for Digital Terrain Model the tree height (H_{max}),
– pixels located below the $0,7 \times H_{max}$ level were rejected,
– for each selected segment, using information about H_{max}, the crown cross-sectional area was estimated in the point tagged as $0,7 \times H_{max}$ level.

The following data, describing individual tree qualifying for the sample, was obtained after conducting the following measurements:

– tree height,
– height above ground level of the lowest observed part of the crown,
– crown cross-sectional area at height equal to 0,7 of the tree height, that is consistent with theoretical height of a crown placing in a dense forest stand,
– maximum crown diameter in the place where the cross section was performed.

Based on the calculations on presented data, variables on individual sample plots were estimated (Fig. 3).

Calculation of the relationship between standing volume and stem density on the ground sample plots and variables obtained from a Canopy Height Model (CHM)

We calculated multiple regression by assuming that one of variables of interest obtained from ground-based measurements of sample plots and referred to 1 ha (a merchantable timber volume V or the number of all trees ZAG) is dependent variables, and variables calculated on the base of the Canopy Height Model (in the spots where the ground sample plots were projected) are independent ones. We used a quadratic function of independent variables which in case of two variables t and z has a general form:

Figure 2. Canopy Height Model, bright tones are referring to tallest trees, dark – ground, herbaceous vegetation or understory stand layers (seedlings, saplings or shrubs)

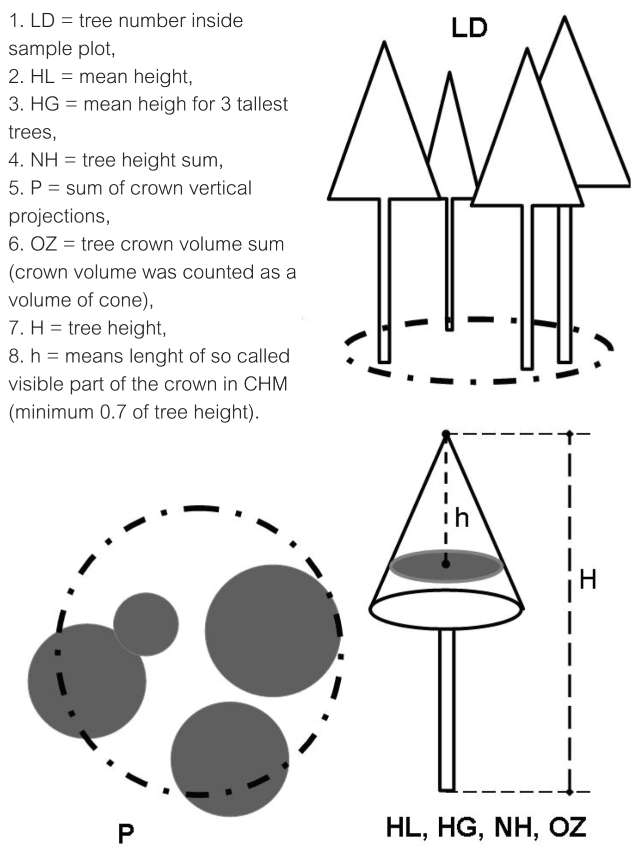

Figure 3. Variables describing part of the stand inside sample plot and rules of calculations some of these features based on Canopy Height Model (CHM)

$$y = a_0 + a_1t + a_2z + a_3t^2 + a_4z^2 + a_5tz$$

A set consisted of three parameters and its adequate squares and pairs of products were used as independent variables. Three parameters were applied, since each of six indicated ones obtained from a Canopy Height Model had one related equivalent. Therefore, alternative pairs were:

– HL and HG,
– LD and NH,
– P and OZ.

Hence, eight combinations of base parameters were set. Selection of variables was due to stepwise backward regression, using the 'Statistica' program.

The aforementioned calculations were performed four times. We took into consideration that independent variables differed according to both the sample size and the means of qualifying trees (crowns) for the sample.

3. Results

Calculation of the relationship between standing volume on the ground sample plots and variables obtained from a Canopy Height Model (CHM)

Strength of the relationship between the standing volume *V* on the ground sample plots and parameters indicated for a Canopy Height Model was different according to the plot size and a way of qualifying trees for the sample. The strength of the relationship was the highest in the "centroid 500 m^2" plot, and the smallest one in the "border 1963,5 m^2" plot (Table 2). In general, the correlation can be valued as very strong. The highest value of the correlation coefficient was R=0,925

($p<0,001$). The results for the best regression model of the “centroid 500 m^2” plot have been presented in Figure 4. Negative values resulted from using a relatively simple model. To avoid it, using data transformation or the regression model without a free parameter is advisable.

For the “centroid 500 m^2” sample plots, especially three sets of variables were useful. Parameter OZ (total tree crown volume) was present in all models. Also HG (height for 3 tallest trees) or HL (height) and LD (tree number inside the sample plot) or NH (total height of trees)) can be recognized as equally useful.

Calculation of the relationship between stem density on the ground sample plots and variables obtained from a Canopy Height Model (CHM)

The strength of the relationship between stem density ZAG on the ground sample plots and that estimated using the results of segmentation on the Canopy Height Model differed and depended on the plot size and the means of qualifying trees for the sample. In case of the standing volume, the correlation was strongest for the “centroid 500 m^2” plots (the highest result for the

Tables 2. The results of multiple regression calculations describing the relationship between standing volume estimated based on ground sample plots measurements *V* and variables taken from Canopy Height Model. Four types of sample plots *a* different in size were used (equivalent to the field) and the way-off qualification trees to the sample (strongest correlations were highlighted using bold font).

The proposed variables (+ their squares and pairs of products)	The size and type of sample plots established for CHM			
	by centroid – 500 m^2	by border – 500 m^2	by centroid – 1963,5 m^2	by border – 1963,5 m^2
	selected variables, the last line – the correlation coefficient R			
HL, OZ, NH	HL^2, OZ^2, HL×OZ, HL×NH 0,915	OZ, HL×NH, OZ×NH 0,871	HL^2, HL×OZ, HL×NH, OZ×NH 0,891	HL×OZ, HL×NH, OZ×NH 0,840
HL, OZ, LD	HL^2, OZ^2, LD^2, HL×OZ, OZ×LD 0,924	HL, OZ, LD^2, HL×LD, OZ×LD 0,891	HL^2, OZ^2, LD^2, HL×OZ, HL×LD 0,898	OZ^2, LD, LD^2, HL×OZ 0,856
HL, P, NH	HL^2, P^2, NH^2, HL×P 0,897	HL^2, HL×P, HL×NH, P×NH 0,869	NH, HL×P, P×NH 0,850	P^2, HL×NH, P×NH 0,839
HL, P, LD	P^2, HL×P, HL×LD 0,883	P, HL×LD, P×LD 0,870	HL^2, P^2, HL×P 0,849	P^2, LD, LD^2, HL×P 0,851
HG, OZ, NH	HG^2, OZ^2, HG×OZ, HG×NH 0,922	HG^2, OZ, HG×NH, OZ×NH 0,891	HG, OZ, HG×NH, OZ×NH 0,883	HG^2, OZ^2, HG×NH, OZ×NH 0,863
HG, OZ, LD	HG^2, OZ^2, LD^2, HG×OZ, HG×LD 0,925	HG, OZ, LD, HG×LD, OZ×LD 0,907	HG^2, OZ^2, LD, LD^2, HG×OZ 0,899	HG, HG^2, OZ^2, HG×OZ 0,841
HG, P, NH	HG^2, NH^2, HG×P, HG×NH, P×NH 0,899	HG^2, HG×P, HG×NH, P×NH 0,888	P, HG×NH, P×NH 0,852	HG, P^2, NH, HG×NH, P×NH 0,871
HG, P, LD	HG, HG^2, P, P^2, LD, HG×LD 0,912	HG, P, LD, LD^2, HG×LD, P×LD 0,911	HG^2, P^2, HG×P 0,870	HG^2, P^2, HG×P 0,840

For the variable symbols see Figure 3

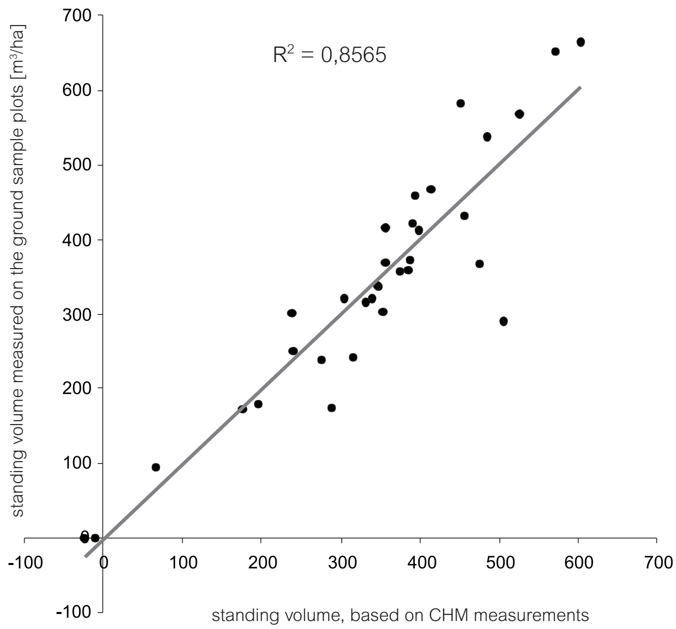

Figure 4. Correlation between standing volume measured on the ground sample plots and calculated for the "centroid 500 m^2" plots based on a Canopy Height Model
(OY – volume based on sample plots measurements,
OX – volume based on CHM measurements)

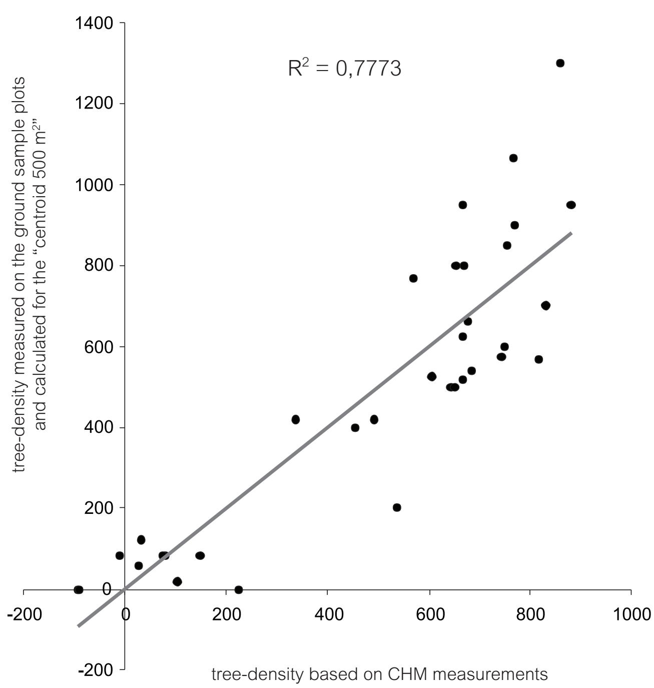

Figure 5. Correlation between tree-density measured on the ground sample plots and calculated for the "centroid 500 m^2" plots with a Canopy Height Model
(OY – tree-density based on sample plots measurements,
OX – tree-density based on CHM measurements).

"border 500 m^2" plot was taken as coincidental), and was lowest for the "border 1963,5 m^2" plot (Table 3). In general, the correlation should be valued as very strong, although, it was weaker when compare to standing volume. The highest value of the correlation coefficient was R=0,888 (p<0.001). The results for the best regression model of the "centroid 500 m^2" plot are presented in Figure 4. Reasons for the appearance of negative values and possibilities for avoiding such a situation can be likely explained in the aforementioned calculations of the standing volume.

HL (mean height), OZ (total tree crown volume), and NH (total height of trees) were the best set of variables for the "centroid 500 m^2" plot. However, changing any of these parameters into HG (mean height for 3 tallest trees), P (total area of crown vertical projections), or LD

Table 3. The results of multiple regression calculations describing the relationship between tree-density estimated based on ground sample plots measurements *ZAG* and density taken from Canopy Height Model. Four types of sample plots *a* different in size were used (equivalent to the field) and the wah-off qualification trees to the sample (strongest correlations were highlighted using bold font).

The proposed variables (+ their squares and pairs of products)	The size and type of sample plots established for CHM			
	by centroid – 500 m^2	by border – 500 m^2	by centroid – 1963.5 m^2	by border – 1963.5 m^2
	selected variables, the last line – the correlation coefficient R			
HL, OZ, NH	HL, OZ, NH, NH^2, HL×OZ 0,882	NH, NH^2, HL×NH, OZ×NH 0,888	NH, NH^2, HL×NH, OZ×NH 0,855	NH, HL×NH 0,795
HL, OZ, LD	OZ, LD^2, HL×OZ 0,865	HL, OZ, HL×OZ, HL×LD, OZ×LD 0,851	LD 0,763	LD 0,773
HL, P, NH	NH, NH^2, HL×NH, P×NH 0,868	NH, NH^2, HL×NH, P×NH 0,864	NH, HL×NH 0,796	NH, HL×NH 0,795
HL, P, LD	P, HL×P 0,840	HL^2, P, LD^2, HL×LD, P×LD 0,840	LD 0,763	LD 0,773
HG, OZ, NH	NH, NH^2, HG×NH, OZ×NH 0,852	HG, HG^2, HG×OZ 0,807	NH, NH^2, HG×NH, OZ×NH 0,841	NH, HG×NH 0,796
HG, OZ, LD	OZ, LD^2, HG×OZ 0,863	OZ, LD^2, HG×OZ 0,864	OZ, HG×OZ 0,824	OZ, HG×OZ 0,797
o	P, HG×P 0,811	HG, HG^2, P 0,825	P, HG×P 0,811	NH, HG×P 0,786
HG, P, LD	NH, HG×NH 0,808	P, HG×P 0,811	P, HG×P 0,811	P, HG×P 0,797

For the variable symbols see Figure 3

(tree number inside the sample plot) did not weaken the relationship (Table 3).

4. Discussion

Using stands of the Milicz Forest District for research, we could compare application results of Airborne Laser Scanning with photogrammetric measurements. Taking results of the Canopy Height Model measurements as potential samples of the first phase in a two-phase inventory method, it is possible to compare it with results of similar calculations estimated on aerial photographs in the 1:10 000 scale (Miścicki 2009). In the cited research, measurements of 283 ground sample plots (267 located in over 20-year-old stands) have been conducted in 2005. The same number of photogrammetric sample plots (calculated in the same year, 2005), localized on the spots where the ground plots were projected, has been used. The location of sample plots in 2006, used in our research, was determined by the location of 34 permanent ground sample plots, some of which have been used in the cited research (Miścicki 2009). Therefore, we can assume that the research material was comparable, and hence, results of the research on applying aerial photographs and airborne laser scanning data for inventory of standing volume using combined method (two-phased) are comparable too.

Strength of the relationship (determined by a correlation coefficient) between standing volume calculated on the ground sample plots and variables on the aerial photographs was R=0,830 (Miścicki 2009). It was however lower than in case of calculations based on parameters obtained from the Canopy Height Model (R=0,925).

In the cited research (Miścicki 2009), correlation between stem density on the ground sample plots and variables on photogrammetric sample plots was not calculated. We can only refer to the previous research (Miścicki 2000); however we have to take into account that in 2000, the photogrammetric technique was at a slightly lower stage of development. Hence, better results could have been obtained so far. Regarding density of trees, strength of relationship (R=0,697) was considerably smaller than it was for samples where the Canopy Height Model was used. Performing calculations base on aerial photographs, stand age was recognized as an additional variable. It was however not used in our research.

Variables applied to determine standing volume were similar to the ones used by other authors (Hyyppä et al. 2006, 2012; Straub, Koch 2012). Unlike Straub and Koch (2012), in our research results based on point cloud were not used in building the model. Nevertheless, total tree crown volume information appeared to be significant. To calculate it, data based on a Canopy Height Model (interpolated from airborne laser scanning data) was used.

The strength of relationship between the standing volume measured on the ground sample plots and variables based on the Canopy Height Model, was higher than the relationship between the standing volume measured on the ground sample plots and variables calculated on aerial sample plots measured using photogrammetric methods. It shows that the automation, regarding analyses of results of interpolating airborne laser scanning data, is a new (and better) opportunity for calculations performed by the combined method. For instance, standing volume of the Milicz Forest District of 7599 ha forest area, using 267 ground sample plots (as a part of the inventory performed by the combined method) and 1980 aerial sample plots based on variables determined with a Canopy Height Model, could have been estimated with the error about ±2,6% (p=0,05). This type of accuracy could be very close to the one which was achieved from the forest inventory using 835 ground sample plots. Further increase in the number of sample plots obtained from the Canopy Height Model would improve the accuracy of the inventory. Suggested solution seems possible, because the cost of automatic calculation depends on the number of samples used in the Canopy Height Model in a lesser degree, and it is limited only by the time of processing data. Complete automation of the process, after receiving results from the ground sample plots, would allow estimation of the standing volume of the forest district within a few days.

5. Conclusion

1) It is advisable to use the same size of the sample plots established in the ground as well on the Canopy Height Model. Relationship between standing volume (or stem density) on the ground plots and variables on the Canopy Height Model plots worsened when the latter were larger than the ground ones.

2) "Centroid" method is a better solution of qualifying tree for the sample.

3) Total tree crown volume (OZ) is the variable, calculated on the Canopy Height Model that is especially useful for estimation of the standing volume and stem density. Other variables such as height (HG – mean height for 3 tallest trees or HL – mean height), number of trees inside the sample plot (LD), or the tree height sum (NH) can also be used. They are of the similar importance to the explanation of the relationship between variables measured on the ground sample plots and that obtained from the Canopy Height Model.

Acknowledgements

The presented research in the paper was funded by the General Directorate of the State Forest supporting the project: "Development of standing volume inventory method based on the integration of data obtained by different geomatics techniques", conducted between 2006 and 2008.

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Translated by: Martyna Olszowska